MASTER

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NOTES, WITH ANNOTATED BIBLIOGRAPHY, ON "ACCUMULATED TEMPERATURE" AND CERTAIN RELATED CONCEPTS

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INTRODUCTION

It is to be expected that attempts would be made to express the growth, yield, etc. of commercially important plants in terms of simple meteorological parameters. Air and soil temperatures, or simple functions thereof were naturally amongst the first to be examined in relation to plant response. This memorandum briefly sets out the history of one such effort.

The numbers in the text refer to the annotated bibliography which follows these notes (the references have been arranged chronologically). The bibliography has been compiled from readily accessible sources and whilst by no means complete, it is reasonably comprehensive and should also be an adequate first guide for workers interested in following up the subject.

SHORT ACCOUNT OF THE DEVELOPMENT OF THE CONCEPTS

In the early 19th century there appears to have been a very reasonable assumption that there would exist a "threshold" temperature for a given plant, below which there would be no effective growth. Research workers therefore looked for ways of expressing plant growth in terms of temperature above this "zero".

An important series of papers on the analysis of phenological records in which accumulated temperature is exhaustively examined is due to A. Angot (4). Of these the first and the last, i.e. those appearing in 1882 and 1892, are the most informative for our present purpose. In the earlier paper reference is made to Boussingault (1) who stated that a plant would not complete its cycle of development unless it received a certain total amount of heat. Martins, de Gasparin and de Cantolle (2) showed that the basal temperature was not necessarily 0°C., and in general rather above this although this varied between different species. Later de Gasparin and Herve-Mangon (4) stated that for wheat the appropriate base temperature was 6°C. In the 1892 paper Angot reviewed the results of eleven years' observations. In the course of the work observations on four common trees and a range of cereal crops were analysed. Varying base temperatures, and zero dates were adopted and attention given to various phases in the development of the plant. Accumulated temperatures were computed from daily maxima as well as from daily means on the several bases. In this paper - in which many of the subsequent criticisms were anticipated - Angot concluded that for the species of trees examined the best base temperature was 0°C. measured from the date of the last significant frost. "Accumulated" temperature based on daily maxima gave rather more consistent results than when based on daily means, and the suggestion was made that even better results should be obtained if the temperature sum above the selected threshold for the daylight period only was considered [an idea later developed by Geslin (30)]. He also pointed out that possibly soil temperature at 25 cm. or 50 cm. depth might prove a more efficient parameter.

For cereals, 6°C. and finally 5°C. was adopted as giving the best results, the zero date being December 1st for rye and winter wheat and March 21st for spring barley. Again he suggested that an improvement might arise if temperatures during the day time only were considered.

Angot stressed that no very precise relationships can be expected as many meteorological factors other than temperature influence plant growth and development and furthermore he was drawn to the conclusion that every species of plant

has an inherent mode of development ("une allure propre") independent of climatological influences.

During the same period work on similar lines took place in this country, in particular by Dr Gilbert (see in ref.5) (one of the founders of the Rothamsted Experimental Station) who examined in the first instance the meteorological records for Greenwich for the period 1852-78 in relation to the wheat crop. Gilbert experimented with many zero dates but throughout seems to have adopted 42°F. as his zero temperature. In 1878, Lt. Gen. Sir Richard Strachey published a paper as Appendix II to the Quarterly Weather Report entitled "The computation of the quantity of heat in excess of any fixed base temperature received at any place during the course of the year to supply a standard of comparison with the progress of vegetation". He followed the practice of Angot and others in making calculations with reference to 42°F. In 1884 the Meteorological Office decided to include "accumulated temperature" in its Weekly Weather Report. The base adopted was 42°F., as being nearly equivalent to 6°C. which has been considered by continental writers on these subjects to be the critical value, the temperature above which is mainly effectual in starting and maintaining the growth, and in completing the ripening of agricultural crops in a European climate. The base is also convenient as being 10°F., above the Freezing Point . (Report of the Meteorological Council to the Royal Society. 1884. p.65). In 1890 the earlier accumulated temperature data for 1878-83 were worked up and published. In addition the progressive totals of accumulated temperature from January 1st each year were published. It would seem (5) that the above decision was taken before Gilbert published his results as he continued to draw upon the Weekly Weather Report data up to 1885.

Reference to accumulated temperature continued to be made in the annual reports of the Meteorological Council and in the Report for 1901 there occurs (p.49) the necessary adjustment to the Meteorological Office formulae when base temperatures of 32°F., 52°F. and 62°F. are taken. There was, however, no critical comment on 42°F.- this was regarded as being fully established. Appendix II of the Report for 1904 contains a long historical account of the development of the "Meteorological Office during the past 50 years". Of some direct interest is the reference on p.71 to an article in the J. Royal Stat. Soc. Vol. XLVIII, Part II, wherein the statistical basis of the rules adopted, and still in use, for computations of accumulated temperatures are set out. The Report for 1906 notes the first official representation of the Ministry (then Board) of Agriculture and Fisheries on the Meteorological Council (see pp. 46 et seq.) and in this connexion it may be of interest to note that Curtiss' paper (ref.1) came out in 1905. In the Report a discussion is also included (p.20-21) on an analysis of wheat yield results in E. England. The grouping of stations into "districts" for the Weekly Weather Report was also altered to correspond more closely with the districts of the Board of Agriculture (E. & W.)

The 1924 Report (p.31) mentions that a comparison of methods of calculating "accumulated temperature" had been undertaken and a "Note" on the subject was published. On p.14-15 of the 1925 Report there is an account of the setting up of a "Permanent Committee on Agricultural Meteorology" to advise the Minister of Agriculture. An important decision taken (see p.26) was to institute a series of "Crop Weather Stations" to make appropriate meteorological and botanical observations; "Accumulated temperature" was to be computed and recorded, but there appeared to have been no critical appraisal of the concept nor of the use of 42°F. as a "base".

Nevertheless prior to and since 1925 a great deal of work had been done on the subject by botanists (see refs. 9, 10. 11). Some writers however have used base temperatures differing from 42°F. (e.g. see ref.6) whilst others have used 42°F. to define a "growing season".

In 1928 the Meteorological Office published a compact analysis, based on Sir Richard Strachey's work. Tables for the evaluation of daily values of accumulated temperature were printed on Form 3300 which is still in use.

REMARKS ON PRESENT POSITION

Any assessment of the value of the work on this subject is made difficult by the use of 42°F. as either a "threshold" for active growth or a "base" for "accumulating" temperature. In addition it may also be regarded as the germination temperature for many important indigenous crops (50°F. for example is often quoted in similar circumstances as the appropriate germination temperature for maize and lucerne). Again to the extent that one can use 42°F. as a reasonable base for the start of active growth of many indigenous plants, 48°F. (see ref 9 p.224) may be considered as the temperature below which the activity of "nitrogen-fixing," bacteria is practically nil.

Although mean air and mean soil temperature are very closely linked, it is frequently not clear in many published papers whether air or soil temperatures is being considered, and in general discussion the ambiguity is often overlooked. Clearly in many cases mentioned above, when the question of the movement of liquids through permeable membranes is being considered (e.g. see discussion on van't Hoff's law in ref. 10), soil, and not air, temperature is probably the relevant variable.

In the soil, where there is little incoming radiation, and when moisture conditions are non-limiting, there is some reason to hope that sums of temperature above an established threshold may prove to be useful parameters.

In the air, especially in relation to plant growth, this no longer true, and it is suggested that "accumulated" temperature is only likely to be a very rough perameter, whose main virtue is simplicity. As a first approximation, methods based on its use may have considerable practical value, but the obvious limitations must be appreciated.

ANNOTATED BIBLIOGRAPHY ON "ACCUMULATED TEMPERATURE" AND RELATED TOPICS

1. Boussingault, M. — Comptes rendus des seances de l'Academie des Sciences. 1re semestre, p.179 Paris 1837.

In this contribution it was stated that the full development of a plant could not take place unless it received a certain total amount of heat.

2. Alph. de Candolle — Geographie bot. raisonnee 1 Chap. II Paris 1855.

In light of work by de Candolle, Martins and de Gasparin, it was concluded that the base temperature was not necessarily 0°C. and moreover varied from species to species.

3. Herve Mangon and de Gasparin — Comptes rendus des seances de l'Academie des Sciences. 2e semestre, p. 823.

For wheat, temperatures above 6°C. should be "accumulated" from date of sowing to full ripening.

4. Angot, A. — Annales Bur. cent. meteor de France

(i) Etude sur la Marche des phenomenes de la vegetation en France 1880-1881.
Annales (1) 1882 pp. B9-72

(ii) Etude etc..... et la migration des oizeaux en France 1882-1883
Annales (1) 1884 pp. B227-287

(iii) " " " " 1884-1885
Annales (1) 1886 pp. B29-76

(iv) " " " " 1886-1887
Annales (1) 1888 pp. B83-132.

(v) " " " " 1888-1889
Annales (1) 1891 pp. B145-188

(vi) Resume des etudes etc. 1881-1890
Annales (1) 1892 pp. B159-210

5. Curtiss, R. H. — Symons' Met. Mag. Vol. 40, Aug. 1905, pp. 113-5

"On the amount of heat required for the growth and ripening of wheat"

Attention is drawn to work by Boussingault (1), Herve Mangon (3), de Candolle (2) on the Continent and Dr. Gilbert in this country.

Wheat was studied. Gilbert adopted a number of empirical procedures to find the best starting date and general air temperature level in an attempt to find a stable "accumulated" temperature sum to time of wheat harvest and found 42°F. the best figure. /This in agreement with Herve Mangon (3)/

Procedure tested by Curtiss from time of sowing to time of harvest at Rothamsted "over a long series of years". Mean value of sum for autumn wheat found to be 1961 day-degrees above 42°F. The greatest variation being from -7% to +8% of this figure. Notes that time interval between sowing and ripening varies by as

much as 7 weeks or 17% of the average period, whereas "differences in accumulated temperature are within 2% of average in 16 out of 28 years studied, ------- and in 8 of remaining years amounts to or exceeds 5%". In some, at least, of these years there was a big divergence from average of other necessary conditions - notably rainfall. He refers also to "temperature results I have similarly obtained for barley".

6. Stapleton, R. G. — Paper read at the Agricultural Meteorological Conference, 1927.

"Effect of meteorological conditions on the amount and nutritive value of pasture and hay"

Weekly winter cuts of Italian Rye-grass show that some growth is maintained at or even below 38°F.

States considerable growth will not commence until temperature adequate.

7. Shaw, W. H. — Man Met. Vol. II, p. 49, 1928

On speaking of the Weekly Weather Report "another special feature is that warmth and cold are not dealt with by the simple process of noting temperatures, but at the suggestion of leading authorities in agricultural science, by "accumulated temperature" above or below 42°F. expressed in "day degrees".

8. Irwin V. and Cochran W. — Suppt. to Roy. Stat. Soc., S(1) 1938 pp. 1-45

"Crop Estimation and its relation to agricultural meteorology"

A comprehensive review of the "Crop Weather" Scheme with particular emphasis on calculation of yields from weather data generally.

"Accumulated temperature" is dealt with incidentally, and the paper is worth consulting for general information on weather-crop relationships.

9. Weaver J.E, and Clements F.E. — Plant Ecology, McGraw Hill 1938, pp.372-5

Discusses straight temperature sum ie. "accumulated temperature" and the exponential (van't Hoff) method.

Notes the need for deciding on a zero temperature and the methods adopted to determine this. Quotes Spring wheat 37°F. corn (maize) 55°F. and cotton 62°F.

Notes that 40°F. and 43°F. have been the most frequently used temperatures.

Quotes work by Livingston & Streve - "The distribution of vegetation in the United States". Carnegie Inst. Washington. Pub. 284, 1921, in which three approaches have been adopted and compared:-

(i) "accumulated temperature"

(ii) van't Hoff's exponential index

(iii) the physiological method, viz. van't Hoff's method with different weighting factors at different temperature levels.

10. Miller, E.C. — McGraw Hill, 1938

"Plant Physiology"

pp.109-111

A discussion on van't Hoff's coefficient. This relates to the increase in permeability of plant membranes for each 10°C. rise in temperature and is obviously related to water and nutrient absorption.

See also pp. 593-4

11. Gardner V.R., Bradford F.C., and Hooker H.D. — McGraw Hill, 1939

"Fundamentals of Fruit Production"

Chapter XIV - Growing season temperatures.

Quotes efforts of a number of earlier workers to establish a zero temperature.

Useful comparison of the efficiency of the straight temperature summation, the exponential method and the physiological method (see ref. 9).

Various thresholds are used and 32°F. seems popular for many fruit trees.

12. Shaw, W.N. — Camb. Univ. Press, 1940.

"Drama of the Weather" (2nd Ed.)

p.143. This is a special view of the effect of temperature which was introduced for the use of agriculture or perhaps for biology generally. It is based upon the idea of the celebrated botanist, de Candolle, that vegetation only 'grows' when the temperature of the air is above 42°F.

13. Lunelund, H. — Helsingfors Comm. Phys. Math. 12, No.10, pp. 43, 1943.

"Uber Klima faktoren und Erntreertrage in Finnland"

For "vegetation" in Finland the author has chosen 3°C. as a base temperature.

14. Conrad, V.C. — Harvard Un. Press, 1944

"Methods in Climatology" (1st Ed.)

p.94. Suggests 43°F. as this is about the "temperature limit of germination of seeds".

15. Geslin, H. — La Meteorologie, 1945, pp.25-41
"Contribution to the study of the Climatology of wheat"
States that 0°C. not 5°C. should be taken as starting point for winter wheat.

16. Nosatorski, A.I. — Doklady Vsesojuz Akad. S-H Nauk. 1946, No. 11-12, 17-20.

"Theoretical considerations for determining the optimum time of sowing winter wheat"

Quotes a total of 580°C to bring about a desired development in plants from sowing to beginning of tillering.

(Here 0°C. is the basal temp. - this has been used also in France w.r.t. certain cereals).

17. Prescott, J.E. — Aus. J. of Science (XI) Aug. 1948

"Response of Growth of Pastures to Temperatures"

Discuss possible relevance of van't Hoff's constant of growth and concludes that between 46°F. and 80°F., the "constant" varies from 2.3 to 3.7.

Seems to lend some importance to 46°F. (about 43°F.)

18. Gens J. de — Landbouwk Tijdschr 60, 236-44, 1948.

"Preliminary investigation on the influence of temperature and rainfall on the yield of permanent grassland."

Quotes good correlation of starch yield on temperature if temperatures lie between 5°C. and 16°C. (i.e. 41°F. to 61°F.).

(Again a "threshold" of about 42°F. for grass)

19. Loewel, E.L. and Bruhn, H. — Mitt. Obst. b. Vers. Jork, 1949, pp.37-8

"Dates of flowering during past 15 years"

Dates of cherry blossoming: only remote link with temperature sum above 0°C.

20. Hansel, H. — Boden Kultur, 1950, 35-43

"The temperature sum as a measure of the growth phase of garden peas, from appearance of cotyledons to flowering"

5°C. (41°F.) used as a basal temperature and day-degrees from 50% germination to 50% of flowering studied. Useful results.

21. Osterwalder, A. — Wadenswl, Schweig Zs. Obst. Weinban, 50, 1951, pp.1-7

"Growth and ripening of fruit and their relation to climate"

Amongst other parameters considers temperature sum above 0°C.

22. Manley, G. — Collins, London, 1952

"Climate and the British Scene"

On p.180 he makes the interesting observation that a mean temperature of 42°F. implies very few nights below 32°F. (at which temperature one might well expect certain vital processes to cease.)

23. Thornthwaite, C.W. — John Hopkins Univ. Lab. of Climatology, N. Jersey, Dec. 1952.

"Temperature relations to time of maturity of crops"

Basal temps. peas 40°F., sweet corn 50°F. (Now superseded by author's evapo-transpiration units but even so temperature sum proved useful in spacing out sowing dates).

24. Rassow, L. — Angew, Met. S. 1952

"Growth zones in Sadsen - Anhalt"

Uses accumulated excess of days above 160 with mean temperature exceeding 5°C.

25. Austin Miller, A. — Metheun, London, 1953

"Climatology"

pp.10: 84-89

Amongst other things emphasises the importance which foresters are attaching to thresholds of (say) 43°F., 50°F.

26. Nuttonson, M.Y. Am. In. Crop. Ec. Wash. D.C. 1953

"Phenology and thermal environment etc."

For wheat, some consistent results by taking accumulated temperature above 40°F. from March 1st

27. Kramer, C. K. Med. Nat. Inst. Wet. Rep. W.R. 54-001 De Bilt

"Heat sum in germination of summer-barley"

In certain circumstances concept useful, e.g. between sowing and brairding of spring barley, heat sum of soil temperatures about 100°C. (from 0°C?)

28. A useful series of older "references" is given in

"The Climate of the British Isles"

by Sharaf A.E. in Bull. de la Soc. Geog. Egypt T.27 pp.211-242, 1954

Author quotes some threshold temperatures - spring wheat 37°F.: oats 43°F.: corn 55°F.: cotton 62°F.

29. Auren T.E., Depkins, S. Arch. f. Geof. 1 Bd. 2, Nr. 4, 91-96 Stockholm 1954

"Insolation as a function of latitude and some conclusions for the growth of plants in Scandinavia"

The growing season is defined by the period with mean (air temperature above 3°C. (40°F.)

30. Gesling, H. La Met. 1954 36, pp.301-7, Paris 1954

"Influence of temperature on the head tallage of wheat"

Temperature (above 0°C.) is combined with a function of daily global radiation and is found to be related to the rate of growth of the leaf.

31. Anderson and Fairbairn Bull. For. Dept. Un. Edin. 1955

"Division of Scotland into Climatic Sub-regions as an aid of Silviculture"

Quotes (p.7) apparently successful attempt by the Norwegian Oscar Hagan in 1931 using 7.5°C. as a basal temperature.

Anderson and Fairbairn prefer 45°F.

32. Growder, L.V. Sell, O.H. Parker, E.H., Madison Wis. Agr. Journal 1955, 47 51-54.

"Effect of clipping, nitrogen application and weather on productivity of fall-sown oats, rye grass and crimson clover"

Number of hours with temperatures above 45°F. was found to be more closely correlated with forage production than the number of hours above any other temperature. This agrees with Blackman's report that the up-take of nitrogen by cereals was higher at 45°F. than at lower temperatures.

33. Wiggans, S.C. Agron. Jour. 1956, 48, pp. 21-25

"The effect of seasonal temperatures on maturity of oats planted at different dates"

Both air and soil temperatures above 40°F. were used.

34. Anon — Farmers Weekly, June 29, 1956

Quotes the use of 42°F. (soil temperatures) in relation to the emergence of the pea-moth from the cocoon.

(There is a considerable literature on the effect of soil temperatures on the life cycle of many insects, but this is regarded as being rather outside the scope of the present memorandum).

35. Nuttonson, M.Y. — American Institute of Crop Ecology, Washington D.C. 1955.

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